EXTENDED PARAMETER STUDY OF THE GIANT IMPACT. A. G. W. Cameron, Harvard-Smithsonian Center for Astrophysics.

My simulations of giant impact scenarios for the formation of the Moon [1–5] have for the most part covered only a limited range of parameter space. With only a few exceptions, the mass of the impactor has been confined to the range 0.1 to 0.2 $M_{\oplus}$ and the angular momentum in the collisions has varied in the range 1–2 times that of the present Earth-Moon system. The total mass of the colliding system has been one $M_{\oplus}$. In general. a low angular momentum collision leads to a circumterrestrial disk of material in orbits mostly confined to within the Roche lobe, but somewhat extending beyond. A high angular momentum collision involves two collisions between the impactor and the target protoearth, as a result of which a substantial body is left in a stable orbit well beyond the Roche lobe. This body is iron-free and is nearly entirely a remnant of the impactor derived from the hemisphere farthest from the protoearth during the second collision. At this stage in the investigation I considered each of these scenarios to be a candidate for the Moon-forming event.

Canup and Esposito [6] have recently investigated the further evolution of the first of these scenarios. the circumterrestrial disk. Such a disk is likely to generate multiple moonlets rather than a single body unless there is a lunar mass of material beyond the Roche lobe with a fairly steep negative surface density gradient; if the single body is to be generated from farther in, then an extremely steep negative surface density gradient is required. Since these conditions appear very improbable, I have initiated a new series of giant impact simulations related to the second scenario.

The first stage of these calculations, nearly complete, involves the assumption of more angular momentum in the giant impact. For this series of runs the impactor was taken to have a mass of 0.3 M and the target protoearth a mass of 0.7 M; the larger impactor mass tends to put more material into orbit in a collision. The angular momentum in the collisions varied from 2 to 4 times that in the present Earth-Moon system. At the upper end of this range the impactor just misses contact with the protoearth, but if it should be molten with little viscosity, then the impactor is severely deformed, some transfer of mass takes place, and the impactor may be captured into an elongated orbit that will lead to subsequent major collisions.

The simulations were carried out using smooth particle hydrodynamics (SPH); there were 5000 particles contained in each of the protoearth and the impactor, and the characteristic smoothing lengths of the particles adjusted themselves during the calculation to maintain mutual overlap with a few tens of their neighbors, in the manner described in [5]. In order to suppress particle evaporation, the initial temperature in the protoearth and in the impactor was set at 1000 K; this is a conservative procedure that makes sure that substantial amounts of energy must be imparted in a collision before an evaporation can take place. The impactor and the protoearth each contained 31 percent iron in the core and the remainder of the mass was in the form of dunite in the mantle. The ANEOS equation of state was used as described in [3]. The impactor and the protoearth were assumed to be at mutual rest at infinity. Previous studies in this series have shown that a positive velocity at infinity does not change the general character of the collisions, although it is likely to prevent a capture in the case where the impactor just misses the target. Preliminary results of the runs completed or nearly so are presented in Table 1.

Table 1 shows the masses and orbital parameters of the principal clumps of material left after the collisions, as selected by visual inspection of the plots. There is no iron in any of these clumps. The runs in Table 1 are listed in order of increasing collisional angular momentum. Increasing amounts of material are left in high orbit as the collisional angular momentum increases. These orbits are stable against tidal disruption as long as their perigees lie above the Roche lobe at slightly less than 3 Earth radii. Three of the fragments listed in Table 1, for runs AM12, AM14. and AM13, have perigees within the Roche lobe and will presumably be disrupted, but the apogees are high enough that the disrupted pieces are likely to collide with other fragments in stable orbits. Although increasing amounts of' materiel are left in orbit with increasing angular momentum, many of the clumps lie on hyperbolic escape orbits in the highest angular momentum cases, so that the amount of material available to accumulate into the Moon actually declines for the highest angular momentum cases. The maximum amount of available material for Moon formation (1.~S lunar masses) is thus at a collisional angular momentum of 2.75 times that of the Earth-Moon system in these runs.

Table 1. Results of the Runs. Angular momentum in units of the Earth-Moon system (3.5×10^{41} cgs), mass in units of the Earth's Moon, and perigee and apogee in units of the present Earth radius. Bound and total mass refer to mass in larger bodies in bound orbits beyond the Roche lobe and to this mass plus that on escape trajectories.

Run	Ang. Mom.	Particles	Mass	Perigee	Apogee	Bound Mass	Total Mass
AM11	2.00	25	0.135	3.95	15.39	0.135	0.135
AM14	2.25	13	0.096	2.35	10.96	0.680	0.680
		93	0.584	4.52	59.17		
AM12	2.50	10	0.049	1.92	688.42	1.606	1.606
		319	1.557	4.51	12.17		
AMI5	2.75	13	0.063		escapes	1.880	1.943
		384	1.880	4.21	16.29		
AM13	3.00	45	0.239	3.51	280.17	1.479	3.166
		65	0.337	3.12	43.90		
		177	0.903	2.03	18.81		
		304	1.633		escapes		
AM16	3.25	32	0.156		escapes	0.870	3.702
		40	0.195	5.17	9.24		
		69	0.337	3.01	30.02		
		68	0.338	3.50	4.94		
		95	0.470		escapes		
		152	0.742		escapes		
		300	1.464		escapes		

Although more than enough material becomes available to form the Moon in the runs with 2.5 Earth-Moon angular momenta or above, there is no reasonable prospect that such high amounts of angular momentum can be removed from the real Earth-Moon system. However, if the giant impact occurred when the protoearth plus the impactor had accumulated a total mass of about half an Earth mass, then a collision equivalent to run AM15 might be expected to produce a Moon with close to a lunar mass in a collision with close to or only slightly more than the present Earth-Moon angular momentum. Future calculations will explore that possibility.

There are many interesting aspects of such a scenario. The Moon would start out iron-tree, and gravitational focusing would bring most subsequently accumulating material into the protoearth, but some iron would accrete to the Moon. The high degree of devolatilization of the Moon probably required that the Moon itself suffered some major collisions with other orbiting chunks of material; such collisions would be common in the higher angular momentum runs followed in this study, in which the Moon itself must be accreted from several massive fragments. The history of the Earth's interior needs to be reconsidered in terms of the role provided by major collisions in producing magma oceans. If, as suggested here, the giant impact occurred when the Earth was about half assembled, then it would become largely molten at that time and core formation would take place, but it is not clear that the magma ocean would stay molten during nearly all of the subsequent accumulation.

This work was supported in part by NAGW-1598 and by NAGW-2277.

References: [l] Benz W et al. [1986] *Icarus, 66,* 515–535. [2] Benz W. et al. [1987] *Icarus, 71,* 30–45. [3] Benz W. et al. [1989] *Icarus, 8l,* 113–131. [4] Cameron A. G. W. and W. Benz [1991] *Icarus, 92,* 204–216. [5] Cameron A. G. W [1997] *Icarus,* in press. [6] Canup R. M. and L. W. Esposito [1996] *Icarus, 119,* 427–446.